LCA Case Studies

Comparative LCA of Industrial Objects

Part 2: Case Study for Chosen Industrial Pumps

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Part 1: LCA Data Quality Assurance – Sensitivity Analysis and Pedigree Matrix
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Part 2: Case Study for Chosen Industrial Pumps
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Preamble: This series consists of two papers which concern the same LCA case study but present two different problems. The first part is devoted to the quality assessment aspects and presents a proposal of the integration of sensitivity analysis and pedigree matrix in one analysis. The second part presents in detail the results of the comparative LCA case study for industrial pumps. The discussed theoretical considerations are implemented.

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Abstract

Goal, Scope and Background. This paper is the second part of the publication which is devoted to comparative LCA analysis of the industrial pumps. The previous paper deals with the methodological aspects concerning quality assessment and forms an independent work. This paper uses practically only the methodological suggestions made there. The main aim of the presented study is to make a comparison between the industrial pumps which are based on two different technologies. The Life Cycle Assessment method is used to check whether the differences of the manufacturing processes influence the level of the potential environmental impact during the whole life cycle of the analysed products.

Methods. The Life Cycle Assessment is carried out using the Ecoindicator99 method. Additionally, an extensive quality analysis of the LCA study is made (Part I). To make the process of an identification of the data easier and faster, they are assigned to a special data documentation form. To ensure the credibility of the LCA results different methods of interpretation are used.

Results and Discussion. The LCA analysis shows clear superiority of the pumps manufactured using modern technology. It seems that this superiority results not only from the differences in the emissions, but also from different characteristics of effectiveness in the usage stage. Thanks to the uncertainty analysis, each LCA result is provided with the range of uncertainty.

Conclusions. The LCA results are supported by different techniques of interpretation: the sensitivity-, the contribution-, the comparative-, the discernability- and the uncertainty analysis. There is strong evidence of the superiority of the pumps based on the modern technology.

Recommendations and Outlook. The main source of the environmental impact in the case of pumps is the usage stage and the consumption of energy. That is why it should be the main area to improve. The LCA results show that actions taken in the usage stage and energy consumption can lead to a considerable reduction of the environmental impacts.

Keywords: Comparative LCA; Ecoindicator99; industrial pumps; life cycle impact assessment (LCIA); life cycle inventory (LCI)

1 Introduction

In this paper, the comparative analysis of the environmental impacts for the industrial pumps is presented. The study is the result of cooperation between the Poznan University of Economics and a big manufacturing company. This company is one of the main manufacturers of the pumps in Poland, especially in the heating and 'in line' pump segments. Each of the analysed products belongs to a certain kind of pumps. The market share of objects represented in the study by pump A1 amounts to about 10 percent and, for the pump B1, the market share equals about 20 percent. Pumps C and D represent old technology and are not produced anymore. Considering little knowledge and willingness on the part of the Polish industry to cooperate in the LCA studies, it is reassuring that the company that participated in this research showed interest in the subject of LCA. For example, only one company has got a Certified Environmental Product Declaration so far [1]. On the contrary, research institutions show growing interest in the LCA studies. In this work, the intended application of the LCA results is marketing and public communication purposes, so the efforts are taken to meet the requirements for the external applications described in the ISO standards series 14040 [2]. A wide quality analysis is performed and presented in the separate article [3]. In this paper, only the direct results will be shown, without making any deeper insight into the methodological solutions.

2 Goal and Scope Definition

The main aim of the study is the comparison of products by identifying, evaluating and quantifying the potential environmental impacts generated during the whole life cycle. For this purpose of the study, six objects, i.e. industrial pumps, are chosen. Four of them represent older technology (A2, C, B2, D) and the remaining objects represent modern technology (A1, A2). The differences in the manufacturing processes are especially related to the methods of the metal casting and the furnace heating. The major point of interest is to answer the following question: can changes

Table 1: Decisions made in the goal and scope definition phase

Objects of the study	Industrial pumps: A1, B1 (modern technology) A2, B2, C, D (older technology)
Goal of the study	Comparative analysis with the intended external application of the results (marketing)
Life cycle stages included	Production (as Assembly), Usage, Final Disposal
System boundaries	Third-order processes included; exclusions based on results of the sensitivity analysis
Function	Pumping of a liquid with a certain temperature and pH during some period of time
Functional unit	Pumping of the 1x 10^7 m^3 water with temp. 100° C and pH 6-8, during 50000 hours of work
Calculation method	Ecoindicator99 using the SimaPro5.0 programme
Verification of results	Sensitivity analysis (changes in: methodology, value choices, functional unit, input data), comparative analysis, discernability analysis, contribution analysis
Data Quality assessment	Sensitivity analysis and Pedigree Matrix (DQI, DQG, DQD, Quality Classes), probability distributions and Monte Carlo simulations

in the production be reflected in the differences of the environmental impact? The comparison is made for the pairs of the pumps chosen from the same group (type) of the objects with similar technical parameters. Thanks to this, it is guaranteed that any difference in the environmental impact is only the result of the qualitative change (different materials used for the same elements) in the structure of the pumps. As one of the last steps (not presented here) the comparison between two pumps of different sizes is also made to check what changes in the LCA results it may lead to. These types of objects usually have different technical parameters which often lead to completely different reference flows. In this study, the life cycle of each pump is divided into three stages: the production (as the assembly), the usage and the final disposal. For these three stages, the data are collected. The main choices made in the first phase of LCA are presented in **Table 1**.

3 Inventory Analysis (LCI)

In this phase, the LCI models are created. It is very important that the compared systems are similar in the sense of the sophistication (depth of analysis), the level of details and the data quality. In this case, two different periods of time are taken into account (1985–89 and 1995–99) and that is why there are different time requirements for the data. The same unit processes are included in the LCI models for each pump embracing the manufacturing of all materials (with the resource consumption, the emissions, the waste generation, etc) used in the production and the usage stages. In the databases available, there is no data concerning the environmental impact generated during the transport and the final disposal of the used elements of pumps. For this reason, the LCI results for these two stages are simply compared without any modification and any impact assessment. In the case of the transport, a special indicator is introduced to convert different transport characteristics (distance, type and tonnage of vehicles) into one general unit. Details will be presented in the later part of this paper. In the SimaPro 5.0 programme the production stage is usually defined as an assembly. For this reason, the LCI tables with aggregated data concerning production processes of each element are put into SimaPro 5.0 database. The similar approach is used in the case of the usage stage. Efforts are made to collect site-specific data for the most important inputs. For the remaining flows, the general data from the database are used. The level of importance of the inputs is determined using the sensitivity analysis [3].

4 Data and Product Systems

For each object the model of the product system is constructed. To provide comparability almost identical systems in respect of their depth and breadth are modeled. The same (or very similar) processes are included and excluded. For all the pumps, the deepest level reached by the model is the third-order as shown in Figure 1. As the next step, the LCI models are filled by the data. Each data point received a special identification number, which consists of the letters (a symbol of the life cycle stage and a name of the material) and the numerals (a symbol of the process and sub-processes). In **Fig. 1**, the symbols of the processes (and data) are presented in the boxes. Each box represents a number of inputs and outputs. For example, in the case of production stage, the first order data concerns the amounts of all materials necessary to assemble pumps needed to fulfill the functional unit and the reference flow. The next boxes placed on the second order level (Fig. 1) include different inputs and outputs used to manufacture these first order materials. The box with red symbol 2A/A1(A1) will serve as an example to explain the relationship between different levels in the product system. '2A' means that this box represents a second input to the assembly stage. 'A1' informs about the sort of material (here a certain type of cast iron). (A1) symbolizes the type of pump which is analysed (here pump A1 manufactured using modern technology). The box on the next level of the product system with a green symbol of A1 presents all processes (inputs and outputs) connected with the production of the material A1. The next box, with black symbols A1A and A1B, etc., concerns the production of the materials (A, B....) needed for the production of the material A1 (third order level). The data have partly a site-specific character (especially in the production of the most important materials) while remaining ones are general (some part of the second order and all third order data) which are taken from secondary information sources (databases and scientific literature).

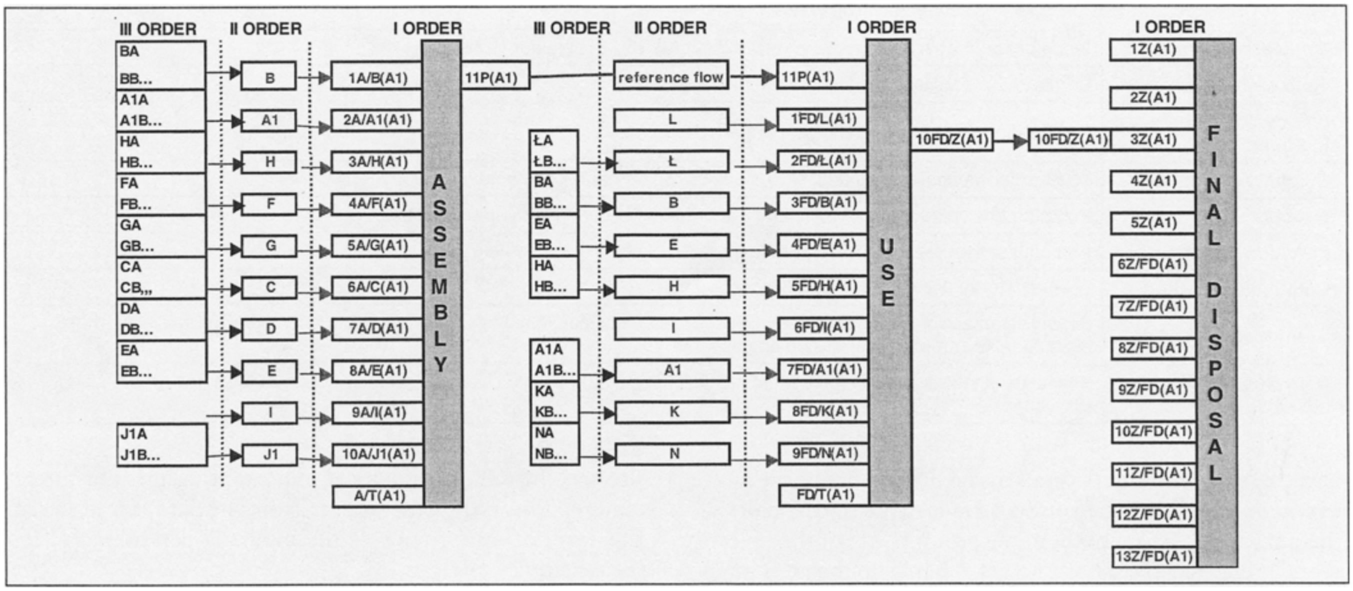

Fig. 1: The product system scheme for pump A1 (with symbols of processes)

About two thousand data are identified, classified and precisely documented. There is a special documentation format prepared [4] which is used for all these data points. This format includes all important information about data as shown in **Table 2**. Thanks to it, very quick identification of each data is possible. Exemplary data documentation format presented below characterizes data points belonging to the production process of material A1. The quality assessment and establishing the quality factors like Data Quality Distance (DQD) and quality classes for the LCA study are presented in a separate article [3]. The results of the assessment are also included in this format. Additionally, process trees which are fulfilled by symbols of data are constructed.

5 Life Cycle Impact Assessment (LCIA)

LCA results obtained in this study are intended to be applied in marketing. In such a case, special requirements defined by ISO have to be met [5]. One of them is avoiding the weighting process. For this reason, the main interpretation is performed on the level of the characterization results (environmental profile) for eleven impact categories. Addition-

Table 2: Data documentation format used in this case study (exemplary for data 1A1a)

General						
Identification Number	**Direction**	**Group**	**Receiving Environment**	**Geographical Location**	**Destination Process**	**Quantitative Reference**
1A1a	input	raw material	technosphere	Poland	production of the casts from the cast-iron	input of raw material
Input Name	**Unit**	**Amount**	**Sample Volume**	**Aggregation**	**Process**	**Technical Scope**
copper	kg	0.105	data point	–	smelting of the cast iron	gate-to-gate
Data Source						
Source	**Name of Source**	**Date of Collection**	**Data Generator**	**Data Archivist**	**Limitations**	**Data Character**
Primary	internal documentation of company	2001–2002	company	casting department	confidential	specific
Data Quality Based on Pedigree Matrix (as DQD and Quality Clases)						
Temporal Correlation	**Geographical Correlation**	**Technological Correlation**	**Completeness**	**Reliability**	**Total DQD**	**Quality Class**
0	0	0	0.6	0.2	**0.8**	**A**
Modelling and Validation						
Basis of Modeling	**Validation Method**	**Allocation**	**Share of the Process A1 in Environ. Impact for Assembly**	**Share of the Process A1 in Environ. Impact for Use Stage**	**DQD for Third Order Data**	**Quality Class for Third Order Data**
process efficiency	mass balance	–	87%	0.039%	1.6	B

Table 3: The characterisation results expressed as the number of the impact categories with the lower value of the indicator results

Pump/MT[a]	Life cycle stage	Number of impact categories with lower values of indicator results	Pump/OT[a]	Life cycle stage	Number of impact categories with lower values of indicator results
A1	Production	10	A2b	Production	1
A1	Usage	11	A2b	Usage	0
A1	Production	9	C	Production	2
A1	Usage	11	C	Usage	0
B1	Production	9	B2b	Production	2
B1	Usage	11	B2b	Usage	0
B1	Production	11	D	Production	0
B1	Usage	11	D	Usage	0

[a](MT) pumps manufactured based on the modern technology and (OT) the older technology

ally, the LCIA results are analysed separately for the production and the usage stages. As mentioned above, the calculation is made using the Ecoindicator99 [6] method and a default hierarchic version. This method is based on the end-points methodology and the results are expressed as the damage indicators for these eleven impact categories (and, after grouping, for three damage categories). The results show a clear superiority of the pumps manufactured by using modern technology in comparison to the 'older' pumps. The superiority means the explicit lower values of the indicator results for all (or almost all) impact categories as shown in **Table 3**. The indicator results for almost all impact categories are lower in the case of the modern pumps. The lower the indicator result, the lower the level of the environmental impact. It means that according to this LCA study, the pumps manufactured by using modern technology lead to the lower potential impact during production and usage stages. These differences are also valid for the final disposal, which will be presented later. To show it in the more detailed way in this paper, the results of the comparison for one of the pairs of pumps only are chosen (B1 and D) and presented in **Fig. 2** and **3**. The results are expressed as percent shares in the indicator results for the

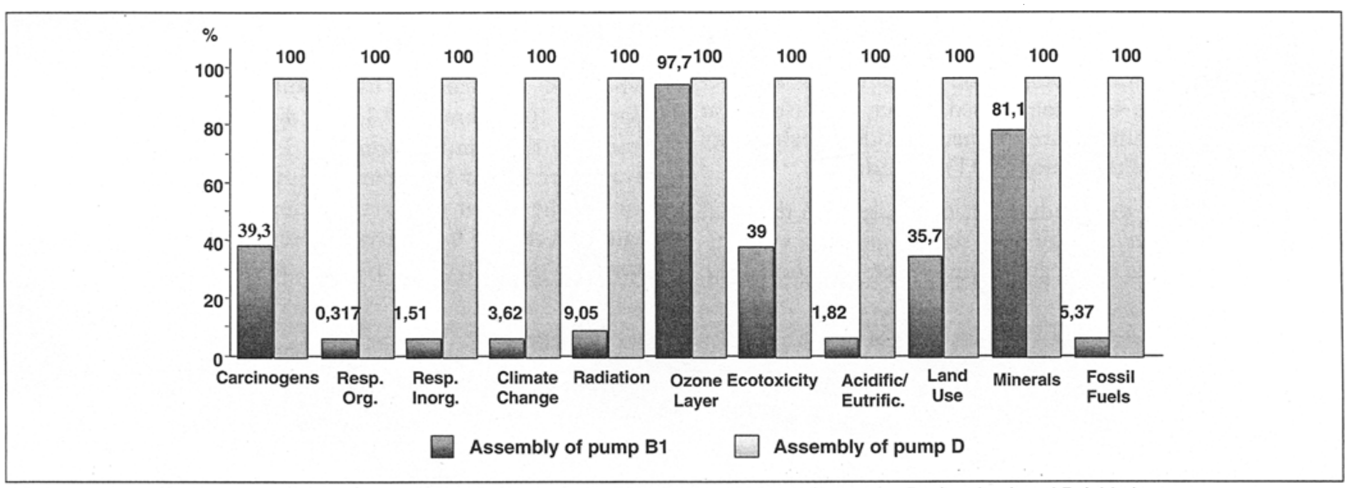

Fig. 2: The exemplary characterisation results for production stage for pumps B1 (modern) and D (older)

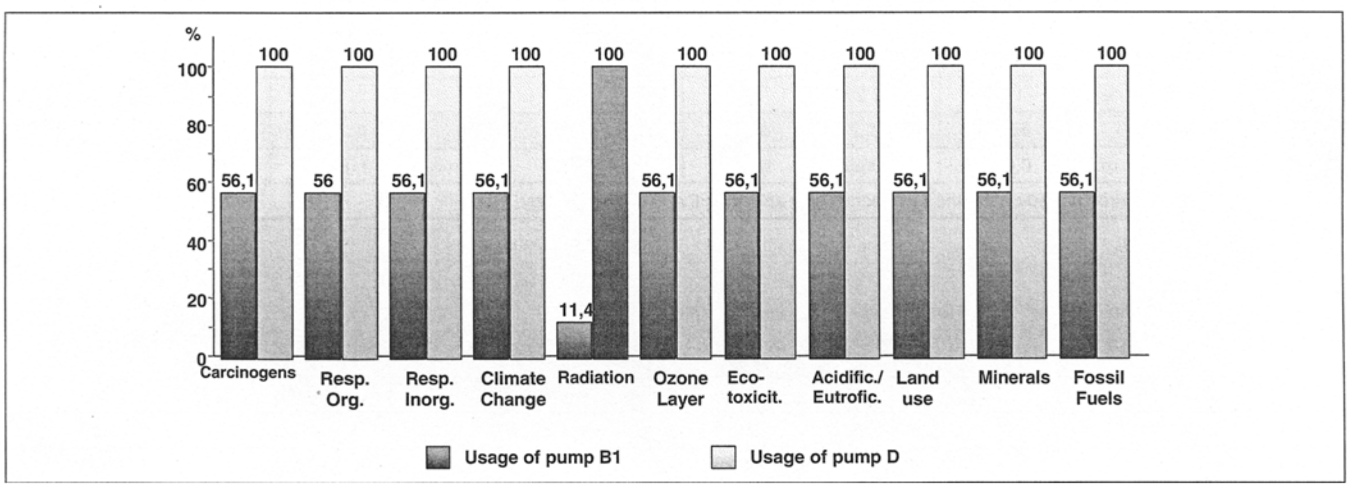

Fig. 3: The exemplary characterisation results for usage stage for pumps B1 (modern) and D (older)

eleven impact categories. The analysis includes all eleven impact categories available in the Ecoindicator99 method. In order to check the results, a different qualitatively sensitivity analysis is performed and the comparison is made using the CML 2000 [7] method and other versions of Ecoindiator99. This way, two different approaches to LCIA methodology are used: a midpoint (CML 2000) and an endpoint (Ecoindicator99) method [8,9]. The calculations confirm the superiority of the modern product systems.

6 Final Disposal and Transport

The Final Disposal stage is analysed in a different way. The lack of appropriate data in the database causes it to be impossible for the full impact assessment to be made. The LCI results expressed as quantity of the used materials, which are intended for the disposal on the landfill, are simply compared. In this situation there is no modelling of the potential impacts and damages, that is why this statement should not be made. The only conclusion that can be drawn is that the product system which generates less quantity of the same type of the waste will probably lead to the lower level of some indefinite impact during the disposal. The type of this environmental impact remains unknown. It is very simple when one product system shows very clear superiority in all the cases of the environmental interventions. But this problem can become more complex if such superiority does not exist. The results of the comparison for all pumps are presented in the **Table 4**. As mentioned earlier, the distinction between pumps manufactured by using modern technology (MT) and the older technology (OT) is made.

The assessment of the production, the usage and the final disposal stages have already been shown, but one very important element has not been presented yet: transport. The information about the environmental impact of the means of transport in question, is not available. For this reason, the analysis, like in the final disposal case, is based on the LCI results. There is, however, some additional difficulty. What method could be used to compare the different types of vehicles and distances? Different means of transport (cars and railway) with the different tonnage (3.5t, 6t, 24t) and distances are analysed. To compare them, one general unit should be introduced. For every pump system and life cycle stage, the quantity of the material and distance are summed up. In this way, the aggregated values are obtained. They are divided into two groups: the road transport and the railway transport. Next, the Transport Factor (TF) is introduced. According to the above distinction, the division of two types of the Transport Factor could be distinguished: for the road transport TF_{RD} and for the railway transport TF_{RW}. It is assumed that the factor depends on two parameters: distance (as the Distance Factor, DF) and load of the transport (as the Load Factor, LF). 1000 kilometres as the standard distance and 3.5 tons as the standard tonnage are assumed. In this way Transport Factor is equal to 1 if the load of 3.5 tons is moved a distance of 1000 kilometres. This relationship can be expressed as follows:

$$TF = DF \times LF \tag{1}$$

where DF is calculated by dividing the obtained distance [km] by 1000 [km] and LF by dividing the obtained load [tons] by the standard tonnage 3.5 [tons]. In this way, the Transport Factor is dimensionless. The higher the value of the TF, the higher the participation of the transport is. The values of the TF for the road and railway transport for the analysed pump systems are presented in **Table 5**.

Table 4: The final disposal stage – the comparison of the LCI results for six analysed pumps

Material	Unit	Pumps			Material	Unit	Pumps		
		A1/MT[a]	A2b/OT[a]	C/OT			B1/MT	B2b/OT	D/OT
Carbon black	kg	0.09	0.14	1.45	Carbon black	kg	–	–	0.335
Rubber	kg	0.05	0.08	1.79	Rubber	kg	0.007	0.009	0.339
Steel	kg	208.55	329.85	69.65	Steel	kg	6.613	8.499	24.121
Copper	kg	5.87	9.29	9.29	Copper	kg	1.185	1.523	2.438
Cast iron	kg	335.88	531.26	435.31	Cast iron	kg	72.590	93.296	120.891
Wood	kg	17.88	28.28	28.28					
SUM		**568.33**	**898.91**	**545.79**	SUM		**80.396**	**103.328**	**148.125**
Lubricant	m3	0,0005	0,0008	0,0008	Lubricant	m3	0,00007	0,0001	0,00015

[a] (MT) pumps manufactured based on the modern technology and (OT) the older technology

Table 5: The values of the transport factors for the analysed pump systems

Pump	TF_{RD}	TF_{RW}	Pump	TF_{RD}	TF_{RW}
A1/MT[a]	2.65	0.015	B1/MT	0.31	0.003
A2b/OT[a]	30.63	5.39	B2b/OT	1.16	0.68
C/OT	11.22	5.49	D/OT	2.29	1.06

[a] (MT) pumps manufactured based on the modern technology and (OT) the older technology

7 Interpretation

In the case of the LCA, there are a few levels of the interpretation. This is connected with the aggregation of the results. The interpretation can be made on the level of the LCI results (here, in the cases of the final disposal and transport), on the level of the characterisation results (environmental profile), and on the further levels of the aggregation: the grouping, the normalisation and the weighting. In the case of Ecoidicator99, there is one more level of results (as the effect of the grouping of the weighted results): level of the Ecoindicator. In the LCA study, different methods of the interpretation are used at all levels of the aggregation (**Table 6**).

A more detailed description of the methods can be found in [10]. Each of the methods makes it easier to understand obtained results. On the one hand, these methods allow identifying the differences in the environmental impact (contribution analysis, comparative analysis, discernability analysis). On the other hand, they can be used to evaluate the credibility and the uncertainty of the results (sensitivity analysis, uncertainty analysis).

8 Results

Some of the results concerning the inventory phase (in the cases of the final disposal and transport) and the impact assessment phase (in the cases of the production and the usage) are presented in the earlier part of this paper in Table 3 and Figs. 2, 3. It allows one to make a statement that the modern pumps A1 and B1 have obvious superiority over the older ones (A2b, C, B2b, D). This is true both in the case of the production and the usage (see Table 3, Figs. 2 and 3), as well as in the cases of the disposal stage and transport (see Table 4 and 5). All the interpretation analyses performed at each level of the aggregation confirm these results and conclusions, but the uncertainty analysis demands special attention. The main aim of the uncertainty analysis is to check whether the obtained results would change if the data uncertainty is included. In the study, at first LCA analysis is performed for the deterministic model with data points and without any knowledge about their uncertainty. Next, using the quality analysis and the values of the DQI, the beta distributions are linked with the input data. From these distributions, two values are derived for every input (a medium one and the value for which there is a probability of 99% that the randomly chosen value would not be higher). These two values for each input parameter are introduced to the SimaPro programme and the new LCA results (on the level of the Ecoindicator) are calculated. This model is called 'transitional' because only the uncertainties of inputs parameters (data) are operational. It is a transitional stage between the deterministic and the stochastic models. In the next phase, the uncertainty analysis is made using Monte Carlo technique. In this situation, both the uncertainty of the input data and the uncertainty of the output results are introduced and quantified. In this manner, the third type of the model (stochastic) is constructed and the third type of the same LCA results is obtained. 500 Monte Carlo simulations are performed and 500 different LCA results are gained. Based on the different 'goodness-of-fit' statistics (tests of normality) it is assumed that they have normal distributions. As in the case of the beta distributions, two values are derived from these normal distributions (medium and P(99%), see before). The comparison of the LCA results from the deterministic, the transitional and the stochastic models is made and presented in **Table 7**. If the results are similar (the same differences and proportions) it could be said that the uncertainty is relatively low. Thanks to the uncertainty analysis, the LCA results can be linked with the ranges of the uncertainty. In this study, the ranges are formed by (+/–) two standard deviations (four sigma). It means that the probability that the wanted value is included in the appropriate range is about 95%. In Table 7, these ranges are presented as the percentage of the results.

9 Commentary

Similar results are obtained from the three different models. In this way, the deterministic results are confirmed by the next more sophisticated analysis. A huge difference between the environmental impact (expressed in points) for the production and usage stage is very visible. In the case of pumps, almost the whole impact is generated in the use stage. For this reason, the impact assessment and interpretation are conducted separately for these two stages. The analysis of the aggregated impact for the whole life cycle (here, production and usage) could lead to the loss of the structure of the impact in the production stage. The environmental superiority of the pumps manufactured by using the modern technology is very clear, both for the full impact assessment in the case of production and usage stages, and also for the comparison of the LCI results in the cases of the transport and disposal. These differences probably result from different characteristics of the efficiency whilst using, which leads to the differences in the reference flows and differences in the structure of the production (natural gas and electricity instead of coal, higher efficiency of the manufacturing processes, lower emissions). It seems that the improvement of

Table 6: Different levels of aggregation of the results and the methods of interpretation used in this study

Step of the LCA	Level of results	Methods of the interpretation
Inventory analysis	Interventions	Contribution analysis
Characterisation	Impact categories	Sensitivity analysis (methodology, functional unit, value choices, criteria of the weighting); Contribution analysis, Comparative analysis
Grouping	Damage categories	Comparative analysis
Normalisation	Normalised profile	Comparative analysis
Weighting	Weighted profile	Comparative analysis
Grouping	Ecoindicator	Sensitivity analysis (data), Comparative analysis, Discernability analysis, Contribution analysis and Uncertainty analysis (Monte Carlo)

Table 7: The results from the deterministic, transitional and stochastic model with the uncertainty intervals

Life cycle stage	Pump	LCA results from three models at the level of Ecoindicator [points]					
		Models					
		Deterministic	Transitional		Stochastic		
		–	Beta distributions		Normal distributions		
		Single points	medium	P(99%)	Medium	P(99%)	Uncertainty ranges (as % of the results)
Production (assembly)	A1	373	375	399	373	395	+/– 5%
	A2b	2117	2120	2260	2116	2218	+/– 4.1%
	C	2192	2270	2330	2187	2295	+/– 4.2%
	B1	15	15	116	15	16	+/– 4.3%
	B2b	257	257	274	257	269	+/– 4.2%
	D	420	389	448	420	440	+/– 4.2%
Use	A1	130056	130000	149000	130102	150146	+/– 13.2%
	A2b	206123	207000	235000	206941	239035	+/– 13.3%
	C	206101	205000	235000	205836	237551	+/– 13.2%
	B1	51402	51300	58800	51436	59365	+/– 13.3%
	B2b	66113	66400	75500	66471	76784	+/– 13.2%
	D	91719	91600	105000	91726	105863	+/– 13.3%

the working efficiency and reduction of the electricity consumption of the pumps is the best direction for their potential development that should be considered by the producer. Similar results are obtained by the other manufacturers of the pumps ITT Flygt [13–15] and Grundfos [16]. The ITT Flygt began working with LCA in 1997 and the programme is now expanded [17]. In this company, the LCA studies are performed by using EPS (Environmental Priority Strategies) method. This research shows also that the main source of impact is the consumption of the energy during the exploitation of the pumps. For this reason, it turned out to be a principle direction of the improvement. There are the intelligent systems of pumps with special microprocessors constructed [15]. Thanks to it, the management of the energy is possible and it seems to be a source of the potential savings (in the long-term perspective) and a reduction of the environmental impact. As the result of this ITT Flygt's work, there are Product Specific Requirements (PRS) prepared for the submersible pumps and mixers [18]. This document is created in cooperation with the main ITT Flygt's competitors ABS AB and Pumpex AB. An other example can be Grundfos company, which has worked with LCA since 2000. To make LCA studies, a tool called EDIP (Environmental Design of Industrial Products, in Danish UMIP) has been used. Based on the LCA results, a clear target has defined. At least 80 percent of new products developed in Grundfos up to 2003 are required to reduce their energy consumption by a minimum of 5 percent compared to the previous models. The decisions about any reduction are made also in other areas: material consumption (production and use stage), final disposal and recycling [16].

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